Figure 9.2 Crystals of natural quartz (SiO_2), one of the most common minerals on Earth. Quartz crystals are used to make special lenses and prisms and are employed in certain electronic applications.

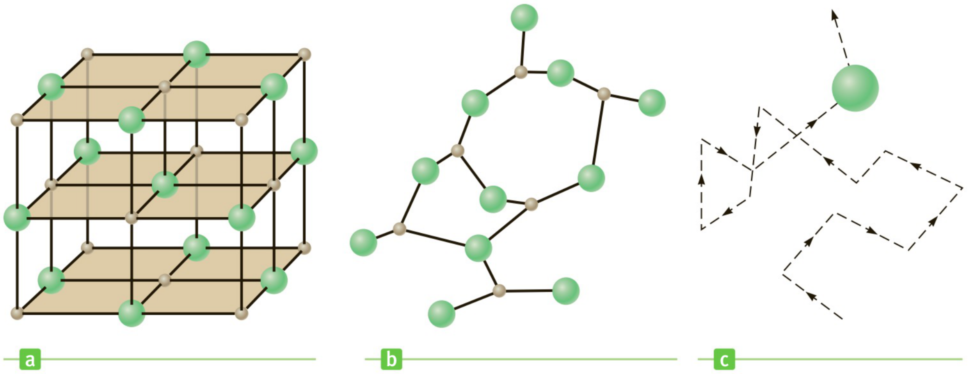

Figure 9.3 (a) The NaCl structure, with the Na^+ (gray) and Cl^- (green) ions at alternate corners of a cube. (b) In an amorphous solid, the atoms are arranged randomly. (c) Erratic motion of a molecule in a liquid.

For any given substance, the liquid state exists at a higher temperature than the solid state. The intermolecular forces in a liquid aren't strong enough to keep the molecules in fixed positions, and they wander through the liquid in random fashion (Fig. 9.3c). Solids and liquids both have the property that when an attempt is made to compress them, strong repulsive atomic forces act internally to resist the compression.

In the gaseous state, molecules are in constant random motion and exert only weak forces on each other. The average distance between the molecules of a gas is quite large compared with the size of the molecules. Occasionally, the molecules collide with each other, but most of the time they move as nearly free, noninteracting particles. As a result, unlike solids and liquids, gases can be easily compressed. We'll say more about gases in subsequent topics.

When a gas is heated to high temperature, many of the electrons surrounding each atom are freed from the nucleus. The resulting system is a collection of free, electrically charged particles—negatively charged electrons and positively charged ions. Such a highly ionized state of matter containing equal amounts of positive and negative charges is called a **plasma.** Unlike a neutral gas, the long-range electric and magnetic forces allow the constituents of a plasma to interact with each other. Plasmas are found inside stars and in accretion disks around black holes, for example, and are far more common than the solid, liquid, and gaseous states because there are far more stars around than any other form of celestial matter.

Normal matter, however, may constitute less than 5% of all matter in the Universe. Observations of the last several years point to the existence of an invisible **dark matter,** which affects the motion of stars orbiting the centers of galaxies. Dark matter may comprise nearly 25% of the matter in the Universe, several times larger than the amount of normal matter. Finally, the rapid acceleration of the expansion of the Universe may be driven by an even more mysterious form of matter, called **dark energy,** which may account for over 70% of all matter in the Universe.

9.2 Density and Pressure

Equal masses of aluminum and gold have an important physical difference: The aluminum takes up over seven times as much space as the gold. Although the reasons for the difference lie at the atomic and nuclear levels, a simple measure of this difference is the concept of *density.*

Density ▶

The **density** ρ of an object having uniform composition is its mass M divided by its volume V:

$$\rho \equiv \frac{M}{V} \qquad [9.1]$$

SI unit: kilogram per meter cubed (kg/m^3)

Table 9.1 Densities of Some Common Substances

Substance	ρ (kg/m^3)[a]	Substance	ρ (kg/m^3)[a]
Ice	0.917×10^3	Water	1.00×10^3
Aluminum	2.70×10^3	Glycerin	1.26×10^3
Iron	7.86×10^3	Ethyl alcohol	0.806×10^3
Copper	8.92×10^3	Benzene	0.879×10^3
Silver	10.5×10^3	Mercury	13.6×10^3
Lead	11.3×10^3	Air	1.29
Gold	19.3×10^3	Oxygen	1.43
Platinum	21.4×10^3	Hydrogen	8.99×10^{-2}
Uranium	18.7×10^3	Helium	1.79×10^{-1}

[a]All values are at standard atmospheric temperature and pressure (STP), defined as 0°C (273 K) and 1 atm (1.013×10^5 Pa). To convert to grams per cubic centimeter, multiply by 10^{-3}.

For an object with nonuniform composition, Equation 9.1 defines an average density. The most common units used for density are kilograms per cubic meter in the SI system and grams per cubic centimeter in the cgs system. Table 9.1 lists the densities of some substances. The densities of most liquids and solids vary slightly with changes in temperature and pressure; the densities of gases vary greatly with such changes. Under normal conditions, the densities of solids and liquids are about 1 000 times greater than the densities of gases. This difference implies that the average spacing between molecules in a gas under such conditions is about ten times greater than in a solid or liquid.

The **specific gravity** of a substance is the ratio of its density to the density of water at 4°C, which is 1.0×10^3 kg/m^3. (The size of the kilogram was originally defined to make the density of water 1.0×10^3 kg/m^3 at 4°C.) By definition, specific gravity is a dimensionless quantity. For example, if the specific gravity of a substance is 3.0, its density is $3.0(1.0 \times 10^3 \text{ kg/m}^3) = 3.0 \times 10^3 \text{ kg/m}^3$.

Quick Quiz

9.1 Suppose you have one cubic meter of gold, two cubic meters of silver, and six cubic meters of aluminum. Rank them by mass, from smallest to largest. (a) gold, aluminum, silver (b) gold, silver, aluminum (c) aluminum, gold, silver (d) silver, aluminum, gold

The force exerted by a fluid on an object is always perpendicular to the surfaces of the object, as shown in Figure 9.4a.

The pressure at a specific point in a fluid can be measured with the device pictured in Figure 9.4b: an evacuated cylinder enclosing a light piston connected to a

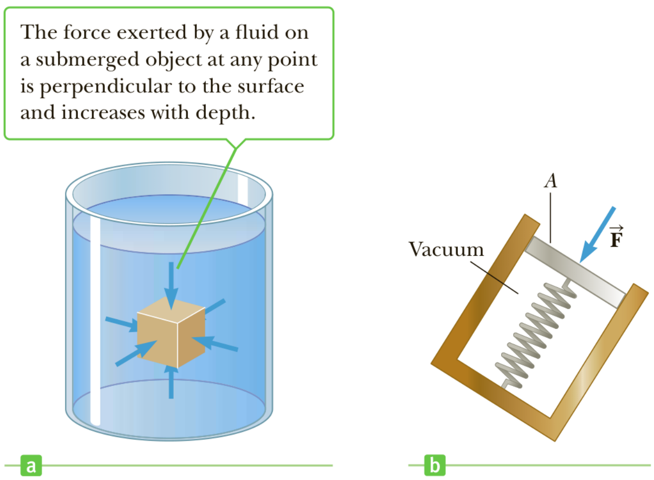

Figure 9.4 (a) The force exerted by a fluid on the surfaces of a submerged object. (b) A simple device for measuring pressure in a fluid.

Tip 9.1 Force and Pressure

Force is a vector and *pressure is a scalar.* There is no direction associated with pressure, but the direction of the force associated with the pressure is perpendicular to the surface of interest.

spring that has been previously calibrated with known weights. As the device is submerged in a fluid, the fluid presses down on the top of the piston and compresses the spring until the inward force exerted by the fluid is balanced by the outward force exerted by the spring. Let F be the magnitude of the force on the piston and A the area of the top surface of the piston. Notice that the force that compresses the spring is spread out over the entire area, motivating our formal definition of pressure:

Pressure ▶

If F is the magnitude of a force exerted perpendicular to a given surface of area A, then the average pressure P is the force divided by the area:

$$P \equiv \frac{F}{A} \qquad [9.2]$$

SI unit: pascal (Pa = N/m^2)

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Figure 9.5 Snowshoes prevent the person from sinking into the soft snow because the force on the snow is spread over a larger area, reducing the pressure on the snow's surface.

Pressure can change from point to point, which is why the pressure in Equation 9.2 is called an average. Because pressure is defined as force per unit area, it has units of pascals (newtons per square meter). The English customary unit for pressure is the pound per inch squared. Atmospheric pressure at sea level is 14.7 lb/in.^{2}, which in SI units is 1.01×10^5 Pa.

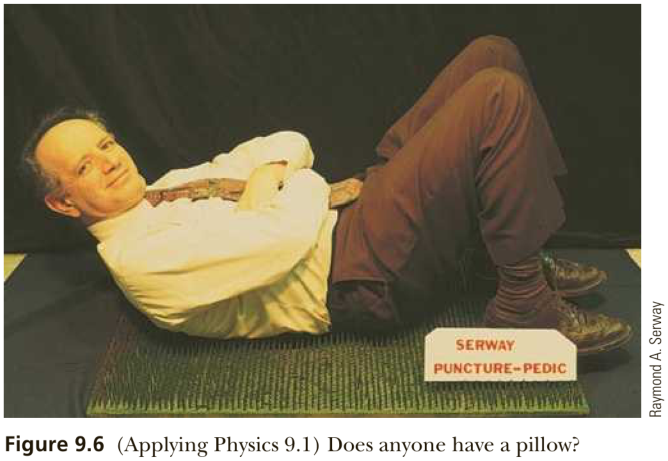
As we see from Equation 9.2, the effect of a given force depends critically on the area to which it's applied. A 700-N man can stand on a vinyl-covered floor in regular street shoes without damaging the surface, but if he wears golf shoes, the metal cleats protruding from the soles can do considerable damage to the floor. With the cleats, the same force is concentrated into a smaller area, greatly elevating the pressure in those areas, resulting in a greater likelihood of exceeding the ultimate strength of the floor material.

Snowshoes use the same principle (Fig. 9.5). The snow exerts an upward normal force on the shoes to support the person's weight. According to Newton's third law, this upward force is accompanied by a downward force exerted by the shoes on the snow. If the person is wearing snowshoes, that force is distributed over the very large area of each snowshoe, so that the pressure at any given point is relatively low and the person doesn't penetrate very deeply into the snow.

APPLYING PHYSICS 9.1 BED OF NAILS TRICK

After an exciting but exhausting lecture, a physics professor stretches out for a nap on a bed of nails, as in Figure 9.6, suffering no injury and only moderate discomfort. How is that possible?

EXPLANATION If you try to support your entire weight on a single nail, the pressure on your body is your weight divided by the very small area of the end of the nail. The resulting pressure is large enough to penetrate the skin. If you distribute your weight over several hundred nails, however, as demonstrated by the professor, the pressure is considerably reduced because the area that supports your weight is the total area of all nails in contact with your body. (Why is lying on a bed of nails more comfortable than sitting on the same bed? Extend the logic to show that it would be more uncomfortable yet to stand on a bed of nails without shoes.) ■



Raymond A. Serway

Figure 9.6 (Applying Physics 9.1) Does anyone have a pillow?

EXAMPLE 9.1 PRESSURE AND WEIGHT OF WATER

GOAL Relate density, pressure, and weight.

PROBLEM **(a)** Calculate the weight of a cylindrical column of water with height $h = 40.0$ m and radius $r = 1.00$ m. (See Fig. 9.7.) **(b)** Calculate the force exerted by air on a disk of radius 1.00 m at the water's surface. **(c)** What pressure at a depth of 40.0 m supports the water column?

STRATEGY For part **(a)**, calculate the volume and multiply by the density to get the mass of water, then multiply the mass by g to get the weight. Part **(b)** requires substitution into the definition of pressure. Adding the results of parts **(a)** and **(b)** and dividing by the area gives the pressure of water at the bottom of the column.

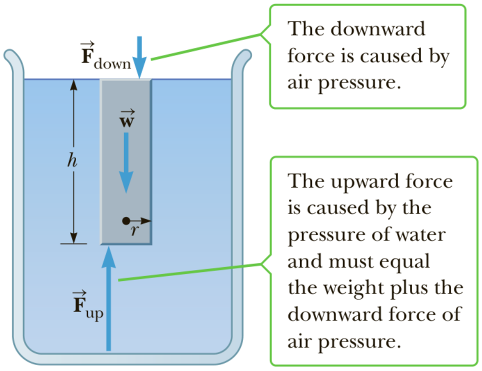


Figure 9.7 (Example 9.1)

SOLUTION

(a) Calculate the weight of a cylindrical column of water with height 40.0 m and radius 1.00 m.

Calculate the volume of the cylinder:

$$V = \pi r^2 h = \pi(1.00 \text{ m})^2(40.0 \text{ m}) = 126 \text{ m}^3$$

Multiply the volume by the density of water to obtain the mass of water in the cylinder:

$$m = \rho V = (1.00 \times 10^3 \text{ kg/m}^3)(126 \text{ m}^3) = 1.26 \times 10^5 \text{ kg}$$

Multiply the mass by the acceleration of gravity g to obtain the weight w:

$$w = mg = (1.26 \times 10^5 \text{ kg})(9.80 \text{ m/s}^2) = \boxed{1.23 \times 10^6 \text{ N}}$$

(b) Calculate the force exerted by air on a disk of radius 1.00 m at the surface of the lake.

Write the equation for pressure:

$$P = \frac{F}{A}$$

Solve the pressure equation for the force and substitute $A = \pi r^2$:

$$F = PA = P\pi r^2$$

Substitute values:

$$F = (1.01 \times 10^5 \text{ Pa})\pi\ (1.00 \text{ m})^2 = \boxed{3.17 \times 10^5 \text{ N}}$$

(c) What pressure at a depth of 40.0 m supports the water column?

Write Newton's second law for the water column:

$$-F_{\text{down}} - w + F_{\text{up}} = 0$$

Solve for the upward force:

$$F_{\text{up}} = F_{\text{down}} + w = (3.17 \times 10^5 \text{ N}) + (1.23 \times 10^6 \text{ N}) = 1.55 \times 10^6 \text{ N}$$

Divide the force by the area to obtain the required pressure:

$$P = \frac{F_{\text{up}}}{A} = \frac{1.55 \times 10^6 \text{ N}}{\pi(1.00 \text{ m})^2} = \boxed{4.93 \times 10^5 \text{ Pa}}$$

REMARKS Notice that the pressure at a given depth is related to the sum of the weight of the water and the force exerted by the air pressure at the water's surface. Water at a depth of 40.0 m must push upward to maintain the column in equilibrium. Notice also the important role of density in determining the pressure at a given depth.

QUESTION 9.1 A giant oil storage facility contains oil to a depth of 40.0 m. How does the pressure at the bottom of the tank compare to the pressure at a depth of 40.0 m in water? Explain.

EXERCISE 9.1 A large rectangular tub is filled to a depth of 2.60 m with olive oil, which has density 915 kg/m^3. If the tub has length 5.00 m and width 3.00 m, calculate **(a)** the weight of the olive oil, **(b)** the force of air pressure on the surface of the oil, and **(c)** the pressure exerted upward by the bottom of the tub.

ANSWERS **(a)** 3.50×10^5 N **(b)** 1.52×10^6 N **(c)** 1.25×10^5 Pa

9.3 Variation of Pressure with Depth

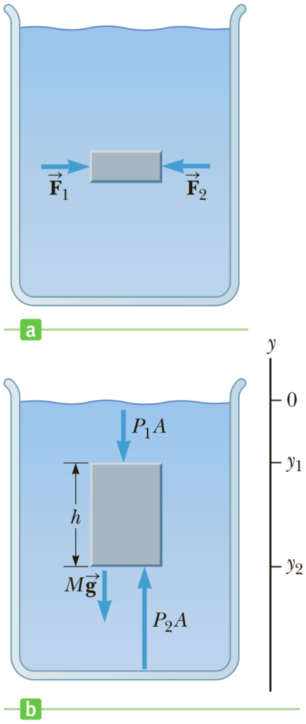


Figure 9.8 (a) In a static fluid, all points at the same depth are at the same pressure, so the force $\vec{\mathbf{F}}_1$ must equal the force $\vec{\mathbf{F}}_2$. (b) Because the volume of the shaded fluid isn't sinking or rising, the net force on it must equal zero.

When a fluid is at rest in a container, **all portions of the fluid must be in static equilibrium**—at rest with respect to the observer. Furthermore, **all points at the same depth must be at the same pressure.** If this were not the case, fluid would flow from the higher pressure region to the lower pressure region. For example, consider the small block of fluid shown in Figure 9.8a. If the pressure were greater on the left side of the block than on the right, $\vec{\mathbf{F}}_1$ would be greater than $\vec{\mathbf{F}}_2$, and the block would accelerate to the right and thus would not be in equilibrium.

Next, let's examine the fluid contained within the volume indicated by the darker region in Figure 9.8b. This region has cross-sectional area A and extends from position y_1 to position y_2 below the surface of the liquid. Three external forces act on this volume of fluid: the force of gravity, Mg; the upward force P_2A exerted by the liquid below it; and a downward force P_1A exerted by the fluid above it. Because the given volume of fluid is in equilibrium, these forces must add to zero, so we get

$$P_2A - P_1A - Mg = 0 \qquad [9.3]$$

From the definition of density, we have

$$M = \rho V = \rho A(y_1 - y_2) \qquad [9.4]$$

Substituting Equation 9.4 into Equation 9.3, canceling the area A, and rearranging terms, we get

$$P_2 = P_1 + \rho g(y_1 - y_2) \qquad [9.5]$$

Notice that $(y_1 - y_2)$ is positive, because $y_2 < y_1$. The force P_2A is greater than the force P_1A by exactly the weight of water between the two points. This is the same principle experienced by the person at the bottom of a pileup in football or rugby.

Atmospheric pressure is also caused by a piling up of fluid—in this case, the fluid is the gas of the atmosphere. The weight of all the air from sea level to the edge of space results in an atmospheric pressure of $P_0 = 1.013 \times 10^5$ Pa (equivalent to 14.7 lb/in.^{2}) at sea level. This result can be adapted to find the pressure P at any depth $h = (y_1 - y_2) = (0 - y_2)$ below the surface of the water:

$$\boxed{P = P_0 + \rho g h} \qquad [9.6]$$

According to Equation 9.6, **the pressure P at a depth h below the surface of a liquid open to the atmosphere is greater than atmospheric pressure by the amount ρgh.** Moreover, the pressure isn't affected by the shape of the vessel, as shown in Figure 9.9. Equation 9.6 is often called the ***equation of hydrostatic equilibrium.*** (Similar, related equations also go by that name.)

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Figure 9.9 This photograph illustrates the fact that the pressure in a liquid is the same at all points lying at the same elevation. Note that the shape of the vessel does not affect the pressure.

Quick Quiz

9.2 The pressure at the bottom of a glass filled with water ($\rho = 1\,000$ kg/m^3) is P. The water is poured out and the glass is filled with ethyl alcohol ($\rho = 806$ kg/m^3). The pressure at the bottom of the glass is now (a) smaller than P (b) equal to P (c) larger than P (d) indeterminate.

EXAMPLE 9.2 OIL AND WATER

GOAL Calculate pressures created by layers of different fluids.

PROBLEM In a huge oil tanker, salt water has flooded an oil tank to a depth of $h_2 = 5.00$ m. On top of the water is a layer of oil $h_1 = 8.00$ m deep, as in the cross-sectional view of the tank in Figure 9.10. The oil has a density of 0.700 g/cm^3. Find the pressure at the bottom of the tank. (Take 1 025 kg/m^3 as the density of salt water.)

STRATEGY Equation 9.6 must be used twice. First, use it to calculate the pressure P_1 at the bottom of the oil layer. Then use this pressure in place of P_0 in Equation 9.6 and calculate the pressure P_{bot} at the bottom of the water layer.

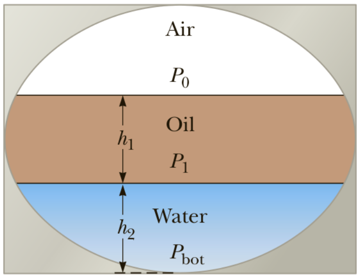

Figure 9.10 (Example 9.2)

SOLUTION

Use Equation 9.6 to calculate the pressure at the bottom of the oil layer:

$$\textbf{(1)}\quad P_1 = P_0 + \rho g h_1$$
$$= 1.01 \times 10^5 \text{ Pa} + (7.00 \times 10^2 \text{ kg/m}^3)(9.80 \text{ m/s}^2)(8.00 \text{ m})$$
$$P_1 = 1.56 \times 10^5 \text{ Pa}$$

Now adapt Equation 9.6 to the new starting pressure, and use it to calculate the pressure at the bottom of the water layer:

$$\textbf{(2)}\quad P_{\text{bot}} = P_1 + \rho g h_2$$
$$= 1.56 \times 10^5 \text{ Pa} + (1.025 \times 10^3 \text{ kg/m}^3)(9.80 \text{ m/s}^2)(5.00 \text{ m})$$
$$P_{\text{bot}} = \boxed{2.06 \times 10^5 \text{ Pa}}$$

REMARKS The weight of the atmosphere results in P_0 at the surface of the oil layer. Then the weight of the oil and the weight of the water combine to create the pressure at the bottom.

QUESTION 9.2 Why does air pressure decrease with increasing altitude?

EXERCISE 9.2 Calculate the pressure on the top lid of a chest buried under 4.00 m of mud with density equal to 1.75×10^3 kg/m^3 at the bottom of a 10.0-m-deep lake.

ANSWER 2.68×10^5 Pa

EXAMPLE 9.3 A PAIN IN THE EAR BIO

GOAL Calculate a pressure difference at a given depth and estimate a force.

PROBLEM Estimate the net force exerted on your eardrum due to the water above when you are swimming at the bottom of a pool that is 5.0 m deep.

STRATEGY Use Equation 9.6 to find the pressure difference across the eardrum at the given depth. The air inside the ear is generally at atmospheric pressure. Estimate the eardrum's surface area, then use the definition of pressure to get the net force exerted on the eardrum.

SOLUTION

Use Equation 9.6 to calculate the difference between the water pressure at the depth h and the pressure inside the ear:

$$\Delta P = P - P_0 = \rho g h$$
$$= (1.00 \times 10^3 \text{ kg/m}^3)(9.80 \text{ m/s}^2)(5.0 \text{ m})$$
$$= 4.9 \times 10^4 \text{ Pa}$$

(*Continued*)

Multiply by area A to get the net force on the eardrum associated with this pressure difference, estimating the area of the eardrum as 1 cm^2.

$$F_{net} = A\Delta P \approx (1 \times 10^{-4}\ \text{m}^2)\ (4.9 \times 10^4\ \text{Pa}) \approx \boxed{5\ \text{N}}$$

REMARKS Because a force on the eardrum of this magnitude is uncomfortable, swimmers often "pop their ears" by swallowing or expanding their jaws while underwater, an action that pushes air from the lungs into the middle ear. Using this technique equalizes the pressure on the two sides of the eardrum and relieves the discomfort.

QUESTION 9.3 Why do water containers and gas cans often have a second, smaller cap opposite the spout?

EXERCISE 9.3 An airplane takes off at sea level and climbs to a height of 425 m. Estimate the net outward force on a passenger's eardrum assuming the density of air is approximately constant at 1.3 kg/m^3 and that the inner ear pressure hasn't been equalized.

ANSWER 0.54 N

Because the pressure in a fluid depends on depth and on the value of P_0, any increase in pressure at the surface must be transmitted to every point in the fluid. This was first recognized by the French scientist Blaise Pascal (1623–1662) and is called **Pascal's principle:**

> A change in pressure applied to an enclosed fluid is transmitted undiminished to every point of the fluid and to the walls of the container.

APPLICATION
Hydraulic Lifts

An important application of Pascal's principle is the hydraulic press (Fig. 9.11a). A downward force $\vec{\mathbf{F}}_1$ is applied to a small piston of area A_1. The pressure is transmitted through a fluid to a larger piston of area A_2. As the pistons move and the fluids in the left and right cylinders change their relative heights, there are slight differences in the pressures at the input and output pistons. Neglecting these small differences, the fluid pressure on each of the pistons may be taken to be the same; $P_1 = P_2$. From the definition of pressure, it then follows that $F_1/A_1 = F_2/A_2$. Therefore, the magnitude of the force $\vec{\mathbf{F}}_2$ is larger than the magnitude of $\vec{\mathbf{F}}_1$ by the factor A_2/A_1. That's why a large load, such as a car, can be moved on the large piston by a much smaller force on the smaller piston. Hydraulic brakes, car lifts, hydraulic jacks, forklifts, and other machines make use of this principle.

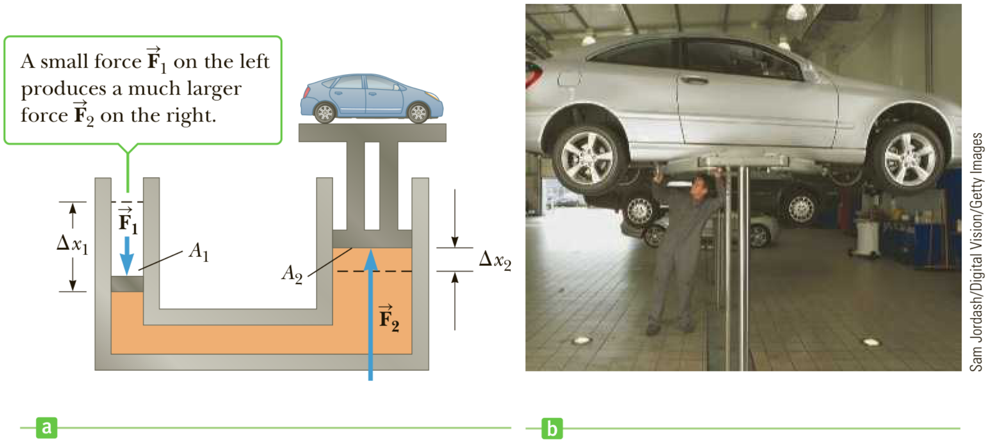

Figure 9.11 (a) In a hydraulic press, an increase of pressure in the smaller area A_1 is transmitted to the larger area A_2. Because force equals pressure times area, the force $\vec{\mathbf{F}}_2$ is larger than $\vec{\mathbf{F}}_1$ by a factor of A_2/A_1. (b) A vehicle under repair is supported by a hydraulic lift in a garage.

EXAMPLE 9.4 THE CAR LIFT

GOAL Apply Pascal's principle to a car lift, and show that the input work is the same as the output work.

PROBLEM In a car lift used in a service station, compressed air exerts a force on a small piston of circular cross section having a radius of $r_1 = 5.00$ cm. This pressure is transmitted by an incompressible liquid to a second piston of radius $r_2 = 15.0$ cm. **(a)** What force must the compressed air exert on the small piston in order to lift a car weighing 13 300 N? Neglect the weights of the pistons. **(b)** What air pressure will produce a force of that magnitude? **(c)** Show that the work done by the input and output pistons is the same.

STRATEGY Substitute into Pascal's principle in part **(a)**, while recognizing that the magnitude of the output force, F_2, must be equal to the car's weight in order to support it. Use the definition of pressure in part **(b)**. In part **(c)**, use $W = F\,\Delta x$ to find the ratio W_1/W_2, showing that it must equal 1. This requires combining Pascal's principle with the fact that the input and output pistons move through the same volume.

SOLUTION

(a) Find the necessary force on the small piston.

Substitute known values into Pascal's principle, using $A = \pi r^2$ for the area of each piston:

$$F_1 = \left(\frac{A_1}{A_2}\right)F_2 = \frac{\pi r_1^{\,2}}{\pi r_2^{\,2}}F_2$$

$$= \frac{\pi(5.00 \times 10^{-2}\text{ m})^2}{\pi(15.0 \times 10^{-2}\text{ m})^2}(1.33 \times 10^4\text{ N})$$

$$= \boxed{1.48 \times 10^3\text{ N}}$$

(b) Find the air pressure producing F_1.

Substitute into the definition of pressure:

$$P = \frac{F_1}{A_1} = \frac{1.48 \times 10^3\text{ N}}{\pi(5.00 \times 10^{-2}\text{ m})^2} = \boxed{1.88 \times 10^5\text{ Pa}}$$

(c) Show that the work done by the input and output pistons is the same.

First equate the volumes, and solve for the ratio of A_2 to A_1:

$$V_1 = V_2 \quad\rightarrow\quad A_1\Delta x_1 = A_2\Delta x_2$$

$$\frac{A_2}{A_1} = \frac{\Delta x_1}{\Delta x_2}$$

Now use Pascal's principle to get a relationship for F_1/F_2:

$$\frac{F_1}{A_1} = \frac{F_2}{A_2} \quad\rightarrow\quad \frac{F_1}{F_2} = \frac{A_1}{A_2}$$

Evaluate the work ratio, substituting the preceding two results:

$$\frac{W_1}{W_2} = \frac{F_1\,\Delta x_1}{F_2\,\Delta x_2} = \left(\frac{F_1}{F_2}\right)\left(\frac{\Delta x_1}{\Delta x_2}\right) = \left(\frac{A_1}{A_2}\right)\left(\frac{A_2}{A_1}\right) = 1$$

$$W_1 = W_2$$

REMARKS In this problem, we didn't address the effect of possible differences in the heights of the pistons. If the column of fluid is higher in the small piston, the fluid weight assists in supporting the car, reducing the necessary applied force. If the column of fluid is higher in the large piston, both the car and the extra fluid must be supported, so additional applied force is required.

QUESTION 9.4 True or False: If the radius of the output piston is doubled, the output force increases by a factor of 4.

EXERCISE 9.4 A hydraulic lift has pistons with diameters 8.00 cm and 36.0 cm, respectively. If a force of 825 N is exerted at the input piston, what maximum mass can be lifted by the output piston?

ANSWER 1.70×10^3 kg

APPLYING PHYSICS 9.2 BUILDING THE PYRAMIDS

A corollary to the statement that pressure in a fluid increases with depth is that water always seeks its own level. This means that if a vessel is filled with water, then regardless of the vessel's shape the surface of the water is perfectly flat and at the same height at all points. The ancient Egyptians used this fact to make the pyramids level. Devise a scheme showing how this could be done.

EXPLANATION There are many ways it could be done, but Figure 9.12 shows the scheme used by the Egyptians. The builders cut grooves in the base of the pyramid as in (a) and partially filled the grooves with water. The height of the water was marked as in (b), and the rock was chiseled down to the mark, as in (c). Finally, the groove was filled with crushed rock and gravel, as in (d). ■

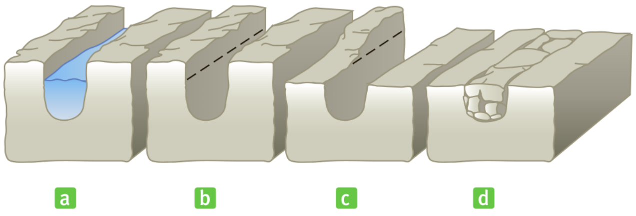

Figure 9.12 (Applying Physics 9.2)

9.4 Pressure Measurements

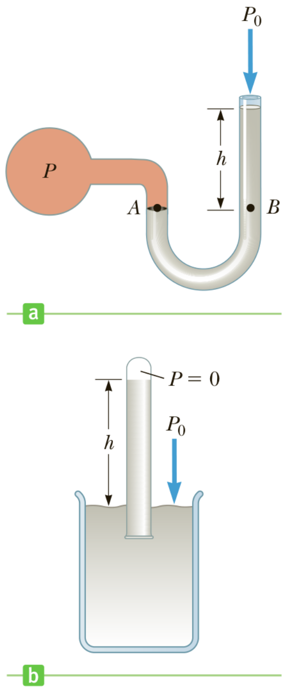

Figure 9.13 Two devices for measuring pressure: (a) an open-tube manometer and (b) a mercury barometer.

A simple device for measuring pressure is the open-tube manometer (Fig. 9.13a). One end of a U-shaped tube containing a liquid is open to the atmosphere, and the other end is connected to a system of unknown pressure P. The pressure at point B equals $P_0 + \rho gh$, where ρ is the density of the fluid. The pressure at B, however, equals the pressure at A, which is also the unknown pressure P. We conclude that $P = P_0 + \rho gh$.

The pressure P is called the **absolute pressure,** and $P - P_0$ is called the **gauge pressure.** If P in the system is greater than atmospheric pressure, h is positive. If P is less than atmospheric pressure (a partial vacuum), h is negative, meaning that the right-hand column in Figure 9.13a is lower than the left-hand column.

Another instrument used to measure pressure is the **barometer** (Fig. 9.13b), invented by Evangelista Torricelli (1608–1647). A long tube closed at one end is filled with mercury and then inverted into a dish of mercury. The closed end of the tube is nearly a vacuum, so its pressure can be taken to be zero. It follows that $P_0 = \rho gh$, where ρ is the density of the mercury and h is the height of the mercury column. Note that the barometer measures the pressure of the atmosphere, whereas the manometer measures pressure in an enclosed fluid.

One atmosphere of pressure is defined to be the pressure equivalent of a column of mercury that is exactly 0.76 m in height at 0°C with $g = 9.806\ 65\ \text{m/s}^2$. At this temperature, mercury has a density of $13.595 \times 10^3\ \text{kg/m}^3$; therefore,

$$P_0 = \rho gh = (13.595 \times 10^3\ \text{kg/m}^3)(9.806\ 65\ \text{m/s}^2)(0.760\ 0\ \text{m})$$
$$= 1.013 \times 10^5\ \text{Pa} = 1\ \text{atm}$$

BIO APPLICATION
Decompression and Injury to the Lungs

It's interesting to note that the force of the atmosphere on our bodies (assuming a body area of 2 000 in.^{2}) is extremely large, on the order of 30 000 lbs! If it were not for the fluids permeating our tissues and body cavities, our bodies would collapse. The fluids provide equal and opposite forces. In the upper atmosphere or in space, sudden decompression can lead to serious injury and death. Air retained in the lungs can damage the tiny alveolar sacs, and intestinal gas can even rupture internal organs.

Quick Quiz

9.3 Several common barometers are built using a variety of fluids. For which fluid will the column of fluid in the barometer be the highest? (Refer to Table 9.1.)
(a) mercury (b) water (c) ethyl alcohol (d) benzene